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THE MYOTRON -- A SERVO-CONTROLLED EXOSKELETON FOR THE MEASUREMENT OF MUSCULAR KINETICS

INTERNAL RESEARCH PROJECT 86-198

FINAL TECHNICAL REPORT

CAL REPORT NO. VO-2401-E-1

MAY 1, 1968

CORNELL AERONAUTICAL LABORATORY, INC.

OF CORNELL UNIVERSITY, BUFFALO, N. Y. 14221

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ABSTRACT

The Myotron is a new type of instrument for the dynamic measurement of skeletal muscle forces and behavior. It is basically a servo-controlled exoskeleton with integral force and position transducers (non-myoelectric). A two-axis instrument was designed and fabricated to establish the practicality and medical utility of such a device. In-hospital evaluation of the instrument as a medical research aid substantiated that the device is potentially suited for basic studies of neuromuscular activity, studies of neuromuscular disorders, development of new rehabilitation therapy techniques, and studies of new powered orthotic devices. This research program (VO-2401-E) was sponsored internally by Cornell Aeronautical Laboratory (authorization 86-198). Medical orientation and evaluation assistance was provided by members of the research staff at the Veterans Administration Hospital, Buffalo, N. Y.

This report introduces the Myotron concept and describes the construction and operational principles of the two-axis instrument. The evaluation experiments and results are presented, with recommendations for further research. A selected bibliography is appended.

ACKNOWLEDGMENTS

The potential benefits of applying the man-amplifier principle to a device for performing medical research were confirmed during discussions between CAL engineers and members of the Veterans Administration Hospital research staff and their consultants. Principal among the contributors were Saul Machover, M. D., then head of the Physical Medicine and Rehabilitation Department, William Walsh, M. D., a research associate in the department and Beverly Bishop, Ph. D., Assistant Professor of Physiology at the State University of New York at Buffalo.

During the development and evaluation phase of the project, continuing encouragement was received from the aforementioned, and assistance and working space was provided by the staff of the Department of Physical Medicine and Rehabilitation, under the acting direction of G. H. Coffey, M. D., in particular Dr. Walsh and Richard M. Johnston, a Research Technician Physical Therapist.

We are pleased to take this occasion to acknowledge their contributions to this program.

CONTENTS

1. INTRODUCTION AND SUMMARY

This report describes the activity and presents the findings of the Cornell Aeronautical Laboratory, Inc. (CAL) internal research project ELBOW, for the development and evaluation of a servo-controlled exoskeleton for the measurement of muscular kinetics. The name "Myotron" was arrived at for this class of device by combining "myo" for "muscle" with "tron" for "electronic instrument". A two-axis Myotron for examining the upper-extremities was designed and constructed to determine the feasibility and utility of this type of instrument, and was evaluated experimentally at the Veterans Administration Hospital in Buffalo. The staff and consultants of the VA Hospital provided medical orientation during both the design and evaluation phases of the program.

Previous research at this Laboratory had studied the problem of amplifying man's natural strength, via an external mechanized structure, in order to permit a person with average strength capability to perform very heavy work tasks with ease. A jointed mechanical body framework, an "exoskeleton", was designed and instrumented to study the structure necessary for such a man-amplifier, and a powered exoskeleton design was completed. Control of the exoskeleton entirely by mechanical force sensors external to the human body was a basic design criteria, thereby avoiding the need for myo-electric control contacts to or under the skin. The concept of a low-power version of man-amplifier emerged from these studies as a potentially useful medical research aid in the field of physical medicine and rehabilitation. Informal discussions with VA Hospital physiatrists confirmed the potential benefits and usefulness of such a research tool.

Thus, in February 1967, Project ELBOW was initiated to design and construct a two-axis powered exoskeleton as a working feasibility model of this medical research-aid concept. The arm was chosen as the limb for study, because the human arm motions are simple in nature, but precisely controlled by complex neuromuscular control processes and would, therefore, potentially yield the most significant medical results. Furthermore, a number of previous neuromuscular studies have considered elbow flexion, and comparison with these early studies was desirable. Elbow flexion-extension and shoulder rotation were chosen as the two axes of movement, thus encompassing both a group of basic limb muscles and a group of basic trunk muscles. (The mechanical structure was devised, however, so that knee flexion and hip rotation could be studied as well.) The basic drive mechanisms and the force measuring transducers were designed to match the strength ability of a normal man's arm and shoulder. A magnetic tape recorder was incorporated to record the measurements, as well as to playback programmed motion sequences for studies of new therapy techniques. Precision analog computer logic and control circuits were designed to enable the servo-mechanisms to be operated in a variety of modes for experiment flexibility and accuracy. Three levels of safety devices were incorporated to minimize the possibility of potentially harmful motions. Fabrication and check-out of the two-axis Myotron was completed in December of 1967.

With the cooperation and medical guidance of the Research Staff of the Physical Medicine and Rehabilitation Department at the VA Hospital, a three-month evaluation of the medical utility of the device was performed. The evaluation was divided into three phases:

1. A study and final adjustment of the subject attachment fittings at the wrist and upper arm, and subject body fixation methods.
2. A study of the control and logic functions under actual test conditions, and
3. A design and study of three separate experimental procedures for the measurement of muscular behavior in hemiplegics.

The results of the evaluation experiments indicate that the Myotron is a powerful new instrument for research in the study of neuromuscular behavior and disorders and that the present two-axis Myotron will be directly useful in three principal areas:

1. measurement of muscular forces under controlled dynamic conditions for basic studies of flaccid and spastic paralysis,
2. study of new therapy techniques, particularly in the management of spasticity, and
3. evaluation of the man-machine interface problems to be encountered with force-following powered orthotic devices.

The remainder of this report contains three major sections. Section 2 describes the physical and electrical units and operating principles of the two-axis Myotron. Section 3 describes the evaluation experiments and their results. Conclusions and recommendations for future investigations are presented in Section 4.

2. MYOTRON DESCRIPTION

A. GENERAL DESCRIPTION

The Myotron is a servo-controlled exoskeleton for the measurement of external forces produced by skeletal muscles under controlled dynamic conditions. A two-axis Myotron was designed and constructed to investigate the utility of such a device as a medical research aid for the study of neuromuscular disorders and as a potential diagnostic or therapeutic aid.

The two-axis Myotron, with the control and recording console, is shown in Figure 1. As presently configured, the device is essentially a powered exoskeleton structure fitted to the human arm, powered to operate in elbow flexion-extension and shoulder rotation while measuring the related muscular forces and limb positions. An earlier unpowered full-body exoskeleton, with thirty-three instrumented joints is shown in Figure 2. This structure has electrical potentiometers at each joint for measurement of position, but the joints are neither controlled nor restrained and force measuring transducers are not employed. The same basic joint construction techniques were employed on the two-axis powered unit, Figure 3, with the mechanical members designed to withstand the mechanical loads capable of being generated by a subject with normal muscular strength.

B. PHYSICAL DESCRIPTION OF THE MAJOR COMPONENTS

The present Myotron is physically composed of three units: the mechanical arm assembly, a support and equipment table, and a portable control console and recorder unit. The arm is securely mounted to the support table, but is adjustable in position to accommodate either right or left arm and any abduction or flexion angle of the shoulder. The arm drive motors are located under the table, and are coupled to the arm drive mechanisms by flexible shafts. The drive components of the arm are shown disassembled in Figure 4. The servo motors and gears, as presently configured, are capable of operation in any 120 degree sector of shoulder rotation, or in any 120 degree sector of elbow flexion (flexion angles greater than 135 degrees anatomical are not allowed due to mechanical interference). The motors can drive both axes at any desired rate up to 100 degrees per second, and can withstand or produce

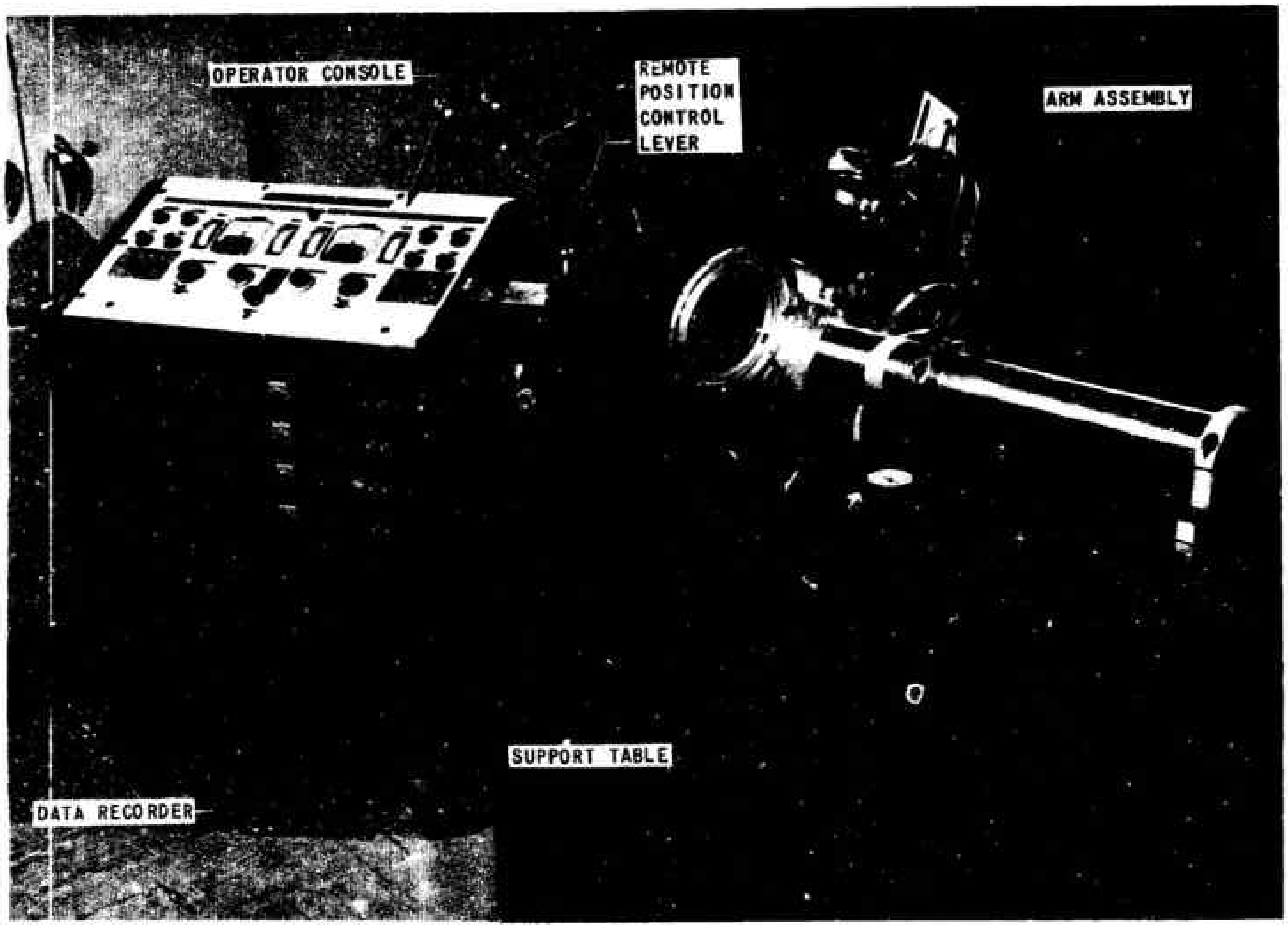

Figure 1 ELBOW MYOTRON AND OPERATOR CONSOLE

Figure 2 UNPOWERED FULL-BODY EXOSKELETON

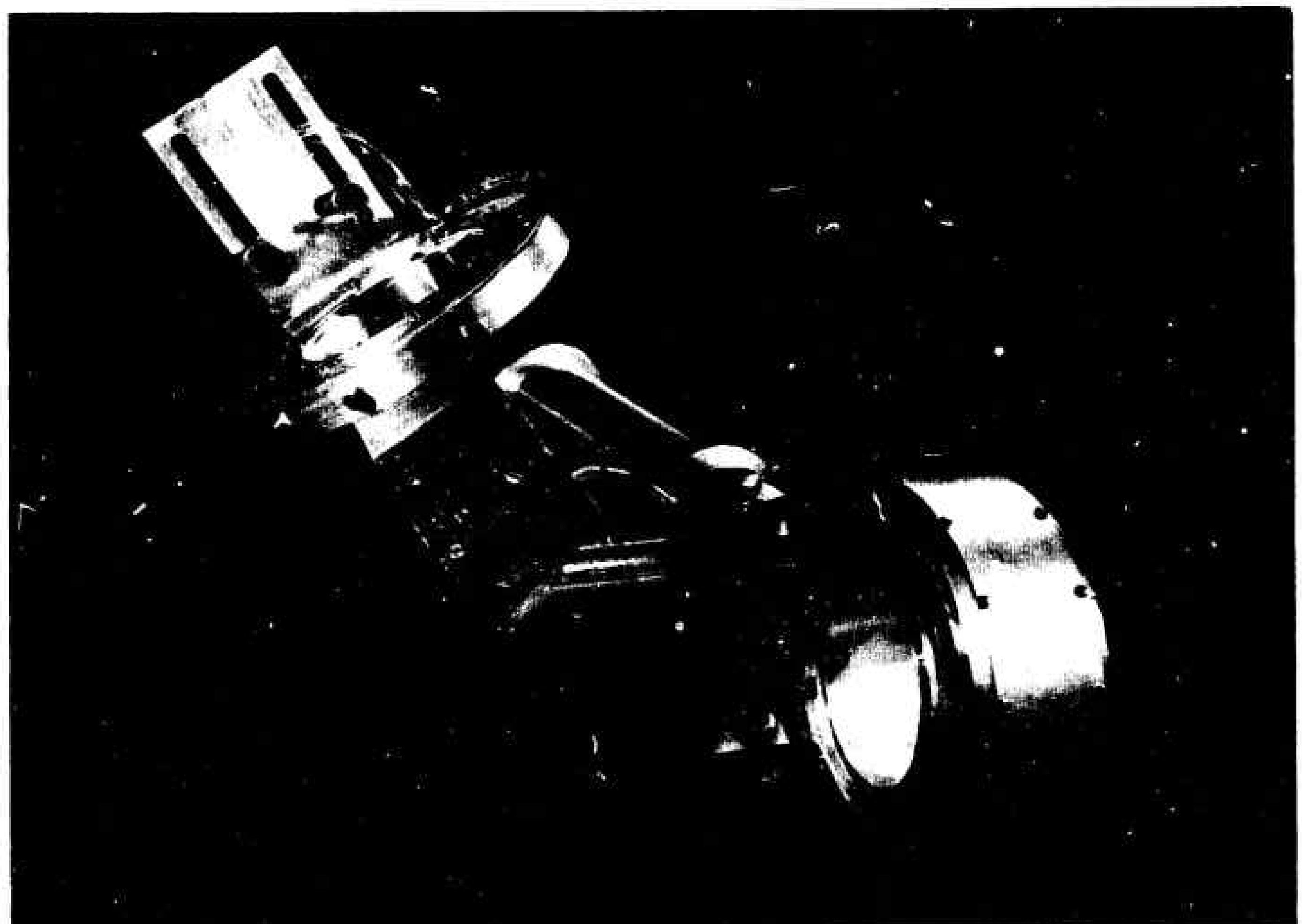

Figure 3 "ELBOW" MYOTRON

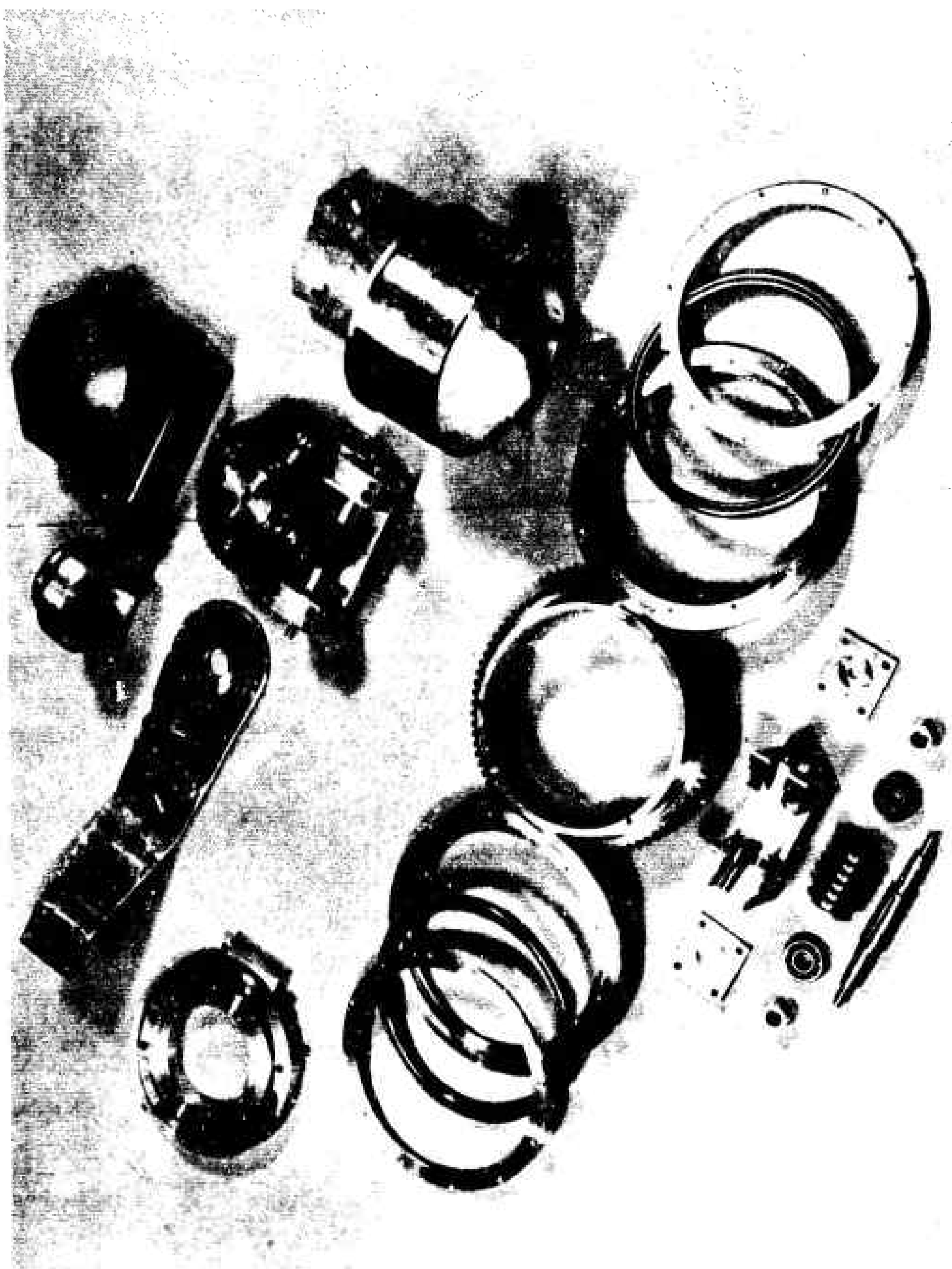

Figure 4 DISASSEMBLED ARM DRIVE MECHANISM

approximately 50 ft-lb of torque.

The subject's arm is inserted into the metal cuff-like supports at the wrist and upper arm. The wrist is secured in the support by a split ring plaster cast. Individual casts are moulded for each subject and serve to distribute the load forces over the wrist surface without discomfort at the wrist protrusions. The cast is inserted into a roller-bearing sleeve ring which allows free rotation (supination-pronation) movement, or the ring may be locked in a fixed position. The upper arm is supported inside the shoulder drive ring sleeve by an inflated cuff which secures the arm, but permits arm volume changes due to muscle contractions.

A force exerted by the subject's forearm against the Myotron structure is measured mechanically as a vector force* at the wrist and converted into electrical signals proportional to this force. A strain-gauge ring, Figure 5, resolves the vector force into two orthogonal components, a flexion-extension component and a rotation component (the rotation component being geometrically aligned for shoulder rotation with the arm flexed to the anatomical 90 degree position). The strain ring is presently capable of resolving force changes of less than 0.03 pounds while measuring forces as great as 100 pounds. The ring contains two sets of four strain gauges, arranged in bridge fashion such that supination-pronation torques and thrust forces do not appreciably affect the desired force measurements.

The arm support table, in addition to providing a solid base for mounting the arm, also houses some of the electrical equipment. The drive servomotors, the high-power servo drive amplifiers and the servomotor power supply are one common equipment group located on a shelf under the table. The strain gauge excitation generator and output preamplifiers are also mounted under the table. Electrical outlets and shelf space are provided for auxiliary experiment equipment such as function generators, oscilloscopes, and emg units.

The portable control console and recorder unit, shown in Figure 1, permits remote control of all the equipment functions from whatever vantage point is

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*Force is the actual measured quantity, and may be converted to torque about the elbow by multiplying the force hy the distance of the strain ring from the elbow, which is approximately 10 inches, but varies with each subject.

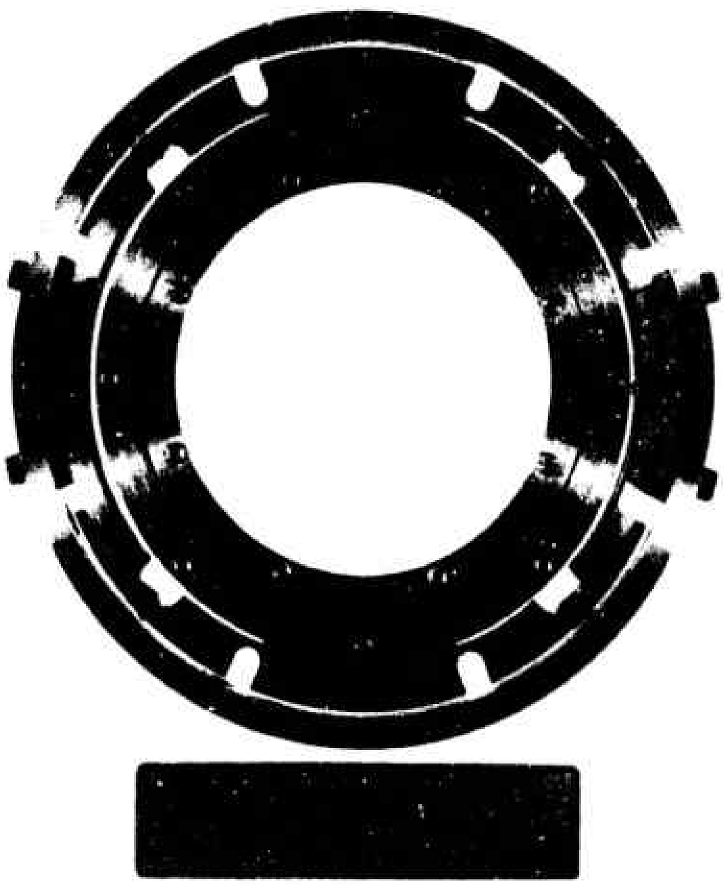


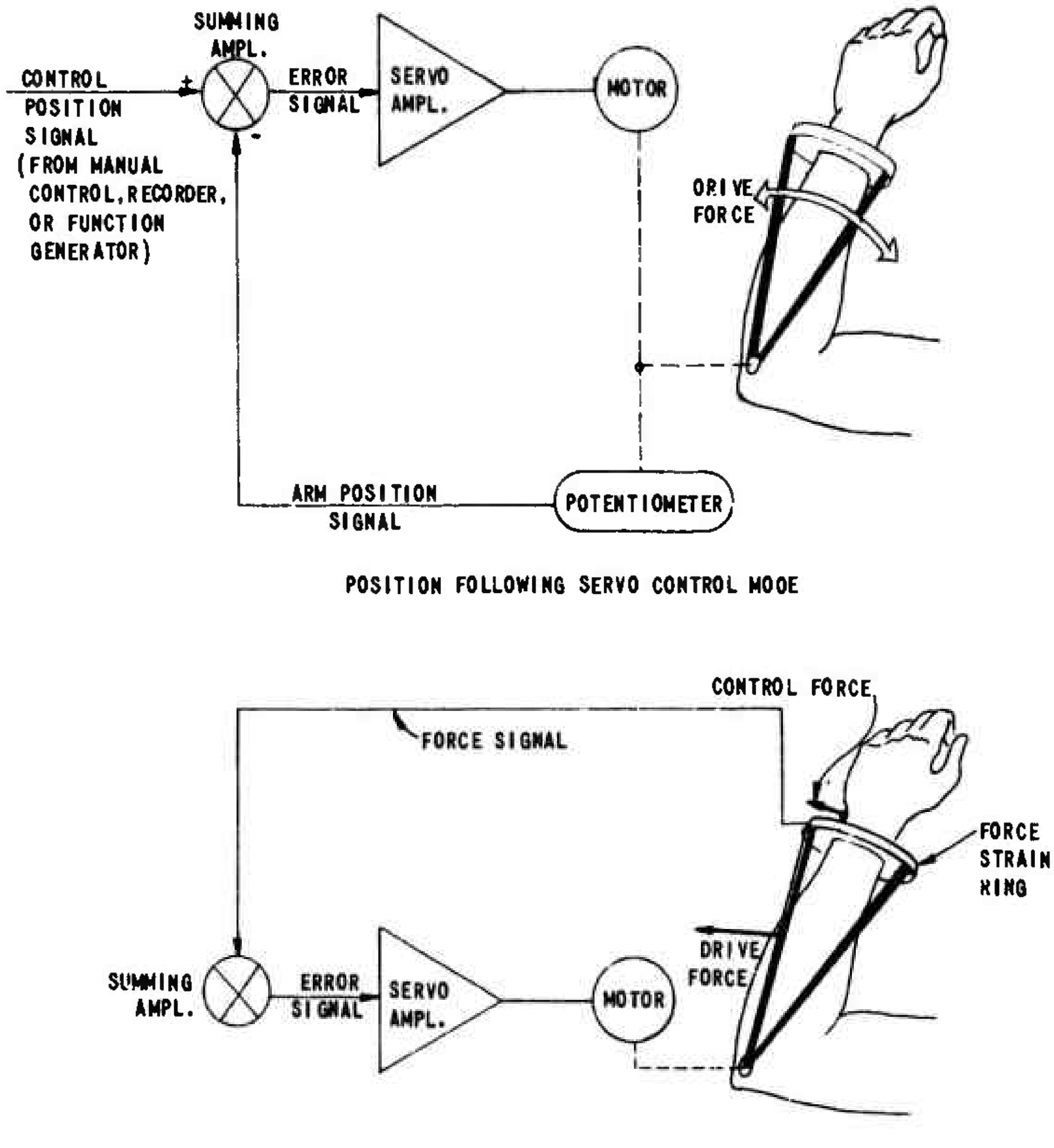
Figure 5 WRIST STRAIN RING CONSTRUCTION

desired by the experimenter. The F-M recording equipment is mounted on a hinged panel at the front of the unit, the controls are located on a sloping console, and the analog computer logic and control circuits are mounted on circuit boards under the control console. A low voltage DC power supply is located behind the recorder panel. Special remote cables are provided to permit the console unit to operate independently of the arm and arm support table for playback of a recorded experiment at any remote location.

C. OPERATING PRINCIPLES

The two powered axes, flexion-extension and rotation, are completely independent in operation, with dual control and measurement instrumentation. Either axis may be operated singly or concurrently in the same or different modes.

All motions of the Myotron are controlled by precision servomechanisms for accuracy and flexibility in performing the experiments. Since both of the basic output parameters, position and force, are measured as electrical signals, either may serve as an input to the servo control circuits, resulting in two basic modes of operation. Figure 6 shows the functional block diagrams for these two basic servo control modes: position-following and force-following. (Only the flexion-extension axis is shown; the rotation axis control is identical.) In the position-following servo control mode, the desired arm position is represented as a d-c voltage control position signal, applied as one input to a summing amplifier. The actual arm position is also represented as a d-c voltage position signal, and is applied as the other input of the summing amplifier, with a sign reversal. Therefore, the output of the summing amplifier is the algebraic difference between the two position signals, or the error signal. The error signal is amplified and used to drive the servomotor in the direction necessary to cause the arm position to match the desired position. When the arm position exactly matches the desired position, the error signal is zero, and the servomotor drive signal is zero. The desired position signal may be derived from the position control lever on the control console, from a position signal pre-recorded on magnetic tape, or from an external voltage source with a scale factor of 12 degrees per volt. This external source typically would be a function generator to cause the arm position to follow a specific function such as a sine-wave or triangular wave. The basic



POSITION FOLLOWING SERVO CONTROL MODE

FORCE FOLLOWING SERVO CONTROL MODE

Figure 6 BASIC SERVO CONTROL MODES

static position accuracy, due to combined system tolerances, is approximately ± 0.5 degrees. The principal dynamic error, proportional to velocity, is less than 2.5 degrees at the maximum speed of 100 degrees per second. However, if the input command signal exceeds this velocity, or the velocity limit setting on the control console, the position lag will increase accordingly. In general, this mode of operation is used for experiments which measure forces as a function of position.

The operation of the Myotron in the force-following mode is analogous from an electrical standpoint. Any force exerted by the subject's arm against the strain ring results in a d-c voltage proportional to the magnitude and direction to the applied force. In this mode, the servomechanism acts as a nulling device, driving the mechanical arm in the direction necessary to reduce or null the applied force. This is accomplished by applying only the d-c force signal to the summing amplifier. Therefore, the servomotor will respond to any detectable force signal. (The most sensitive gain control setting results in arm movement for force levels greater than about 0.03 pound.) Thus when the subject attempts to, say, raise his arm, the force detected as the muscles contract cause the motor to raise the mechanical arm, or to follow the force exerted by the subject. The servomotors will be driven to their maximum velocity for very slight applied forces, so that the arm will follow attempted motions with little effort by the subject. However, if the maximum speed limit (100 degrees per second, or front panel control setting) is exceeded , a marked increase in force will, of course, be measured.

Using analog computer logic techniques, variations may be imposed on this basic force-following mode. The simple addition of a d-c voltage to the summing amplifier results in the addition of a spring-like force to the servo loop. For the system to null, the subjects arm must exert a force to counter the added force, giving the "feel" of pulling against a spring. This voltage counterforce is adjustable in magnitude and direction with a front panel control.

Another logic circuit operation is used to employ a force threshold, whereby the mechanical arm will not follow the intended motion until the force exerted by the subject exceeds some threshold force. This has the effect of adding a resistance to movement, similar to that produced by a slipping clutch, requiring considerable work to reposition the arm. This is accomplished by adding a threshold circuit to the error signal path, requiring that the error signal exceeds the selected threshold to activate the servo amplifier. This threshold level is also selectable with a front panel control.

The simultaneous addition of a counterforce signal acts to bias the threshold, enabling motion in one direction with less resistance than in the opposite direction. In general, the force-following mode of operation is used for experiments which measure position change as a function of force, such as active range of motion studies.

D. OPERATING CONTROLS AND INDICATORS

The controls on the operator console may be functionally divided into two categories: those common to both axes, and those for individual axis control. The individual controls are arranged in three groups: the meters, the operating controls and the safety limit controls. Figure 7 shows the locations of these controls on the operator console.

The controls common to both rotation and flexion-extension axes are listed below.

1. The POWER switch is an illuminated push-on, push-off switch which controls the input 115 VAC power from the line. It is arranged to function as an emergency stop switch, for the motors will brake to a halt within a tenth of a second after the operator pushes this centrally-located, large switch.

2. The RECORD indicator is an amber light indicating that the recorder operating controls are in the record position, and is intended as an operator warning to prevent inadvertent recording on a pre-recorded tape intended for programmed motions.

3. The REMOTE POSITION CONTROL LEVER, located on the side of the control console (see Figure 1) is a gimbal control to simulate and control the possible positions of the arm in flexion-extension and rotation. This control is active only with the control selector switch set to POSITION INPUT.

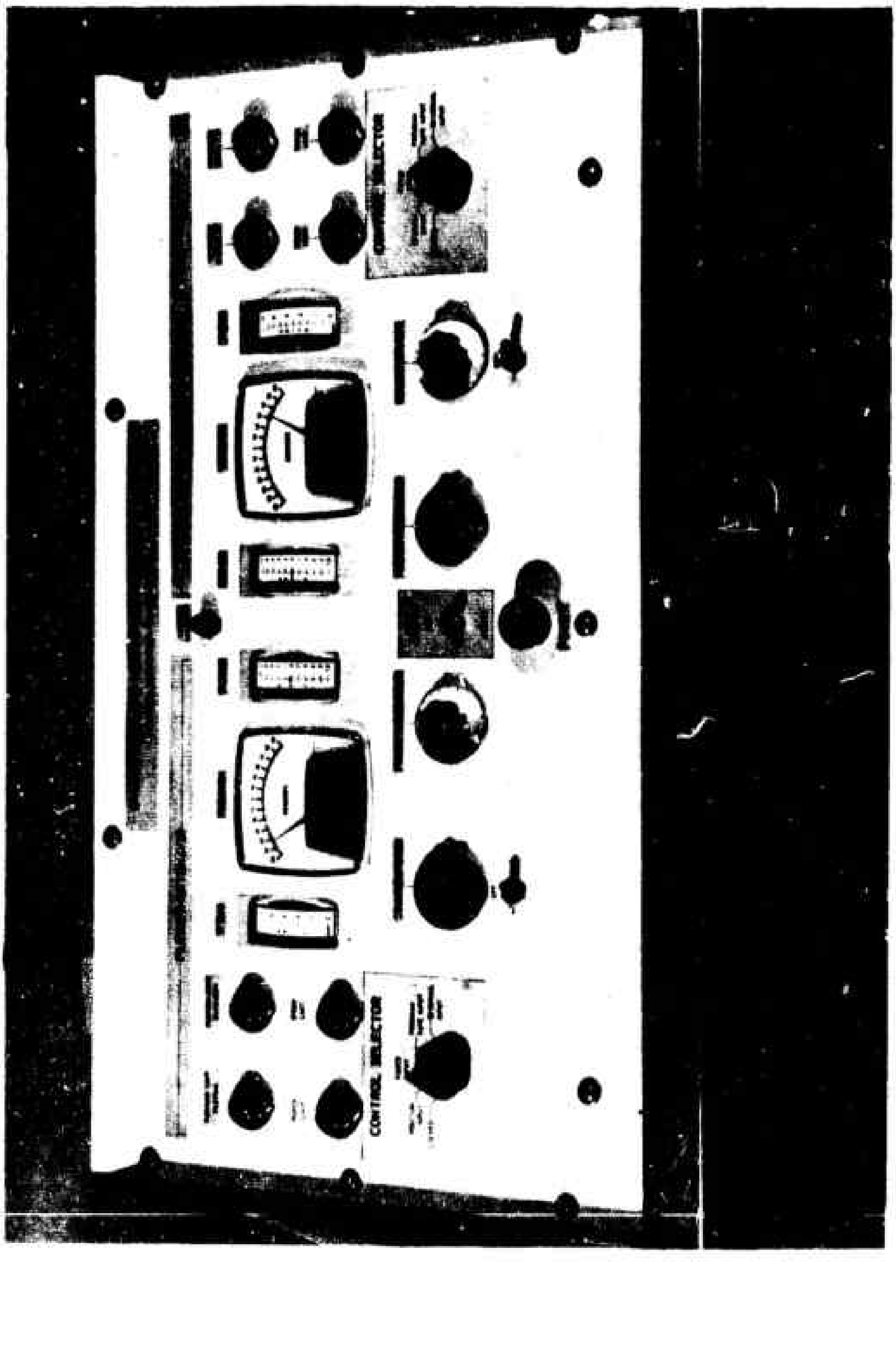


Figure 7 OPERATOR CONTROLS

The controls for the individual flexion-extension and rotation axis are symmetrically arranged on the left and right side of the console. The meter group is listed below.

1. The POSITION meter indicates the arm position in degrees with respect to an arbitrary zero position (normally the center of the possible range of arm travel). Full scale on the meter is $\pm$ 60 degrees.

2. The FORCE meter indicates the force exerted on the strain ring in the direction of axis travel. Full scale deflection is adjustable with the FORCE SENSITIVITY control for any level between three and one hundred pounds. (The single toggle switch sensitivity control shown in Figure 7 was replaced with two individual-axis continuous dial controls for greater flexibility.)

3. The SPEED meter indicates the speed of arm movement in degrees per second, with 100 degrees per second being full scale deflection.

The individual axis operating controls are listed below.

1. The CONTROL SELECTOR switch may be positioned for the following operating modes.

   -- LOCKED - The arm remains locked in the present position.

   -- POSITION INPUT - The arm follows the position of the remote position control lever.

   -- FORCE INPUT - The arm is controlled by the force exerted at the strain ring, and the settings of the counterforce and force threshold controls.

   -- PROGRAM TAPE INPUT - The arm follows the position programmed on the tape recorder. (Recorder preamplifiers must be in the playback mode.)

- EXTERNAL INPUT - The arm follows the position command of the d-c voltage applied to the external input jack, zero volts for center position, 12 degrees per volt sensitivity.

2. The COUNTERFORCE control dial and selector switch determine the level and direction of a constant "spring" force added to the force-following control mode. The dial is calibrated in percent of full scale of the force meter, and the counterforce is indicated on the force meter in summation with the force applied at the strain ring. The center position of the toggle switch is zero counterforce.

3. The FORCE THRESHOLD control dial setting determines the amount of force necessary at the strain ring for the arm to operate in the force-following mode. This is equivalent to a constant "resistance" force. The dial is calibrated in percent of full scale of the force meter.

The safety controls on the front panel are electronic limits for position, speed, and force. These limits are in operation regardless of the control mode selected, and will override any control input signals. Their operation is described below.

1. The two POSITION LIMIT control dial settings determine the maximum arm excursion from the zero degree indication on the position meter. They are individually adjustable for different plus or minus directions, and are calibrated in percent of maximum deflection (60 degrees).

2. The FORCE LIMIT control dial setting indicates the maximum force level attainable while the motors are activated. If that force level is reached, the motor will drive the arm in the proper direction necessary to reduce that force. The dial is calibrated in percent of full scale of the force meter.

3. The SPEED LIMIT control dial setting determines the maximum speed of the arm for any operation, including any switching transients. The dial is calibrated in percent of full scale of the speed meter.

To further protect the subject from unintended and potentially harmful motions, two other safety controls are incorporated. Adjustable mechanical limit switches are positioned on the arm itself, and are connected in such a way that if either the rotation or the flexion-extension angle exceeds the mechanical limits, the drive servomotors are dynamically braked to a halt. The motors cannot be operated until the arm is mechanically re-positioned by manual means to within the prescribed limits. In addition, the subject may be given a hand-operated switch (shown attached to the side of the console in Figure 1) which prevents the motors from operating unless the switch button is depressed. If the subject releases his grip on this switch, the motors are dynamically braked to a halt. (At the discretion of the operator, this switch may be bypassed by removing the cable jack from the control console.)

The tape recorder and preamplifier* controls are pre-set to calibrated settings, except for the playback-record selector switch on the preamplifier, and the tape transport selector on the tape recorder. The tape transport selector combines the stop-play function with the fast forward and rewind functions. The tape recorder uses standard 1/4 inch magnetic tape, and will record for over 45 minutes on one reel. Input and output jacks are provided for monitoring and strip-chart recorder playback of the four channels. The channel assignments are (in order from top to bottom preamplifier) rotation force, flexion extension force, rotation position and flexion-extension position. The input and output sensitivities are $\pm$ 5 volts full scale, and the overall frequency response including the FM modulators and demodulators is from d-c to 3 db down at 60 Hz.

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*Standard 4-tracktype 87 Viking tape transport with type RP83 preamplifiers.

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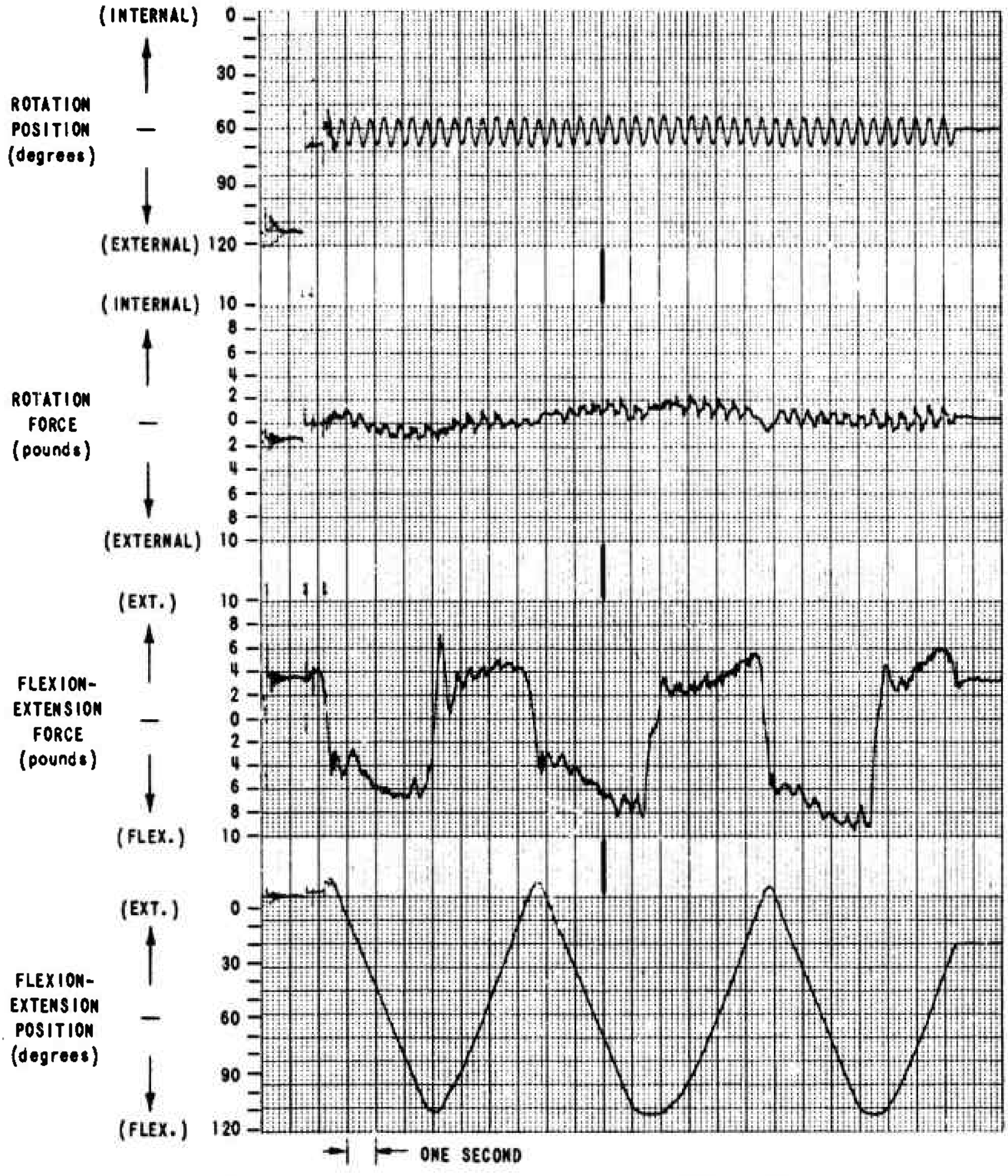
The playback of data from the tape recorder to a strip chart recorder or other display device may be arranged in a number of possible formats. A typical arrangement for a strip chart recorder playback is shown in Figure 8.



NOTE: TEST CONDITIONS -- FORCE FOLLOWING SUBJECT'S FLEXION-EXTENSION MOVEMENTS WITH VELOCITY LIMIT IMPOSED AND TWO-HERTZ POSITION DITHER APPLIED TO ROTATION AXIS. (SUBJECT NORMAL)

Figure 8 MEASURED PARAMETERS -- TYPICAL PLAYBACK FORMAT

E. CIRCUIT DESIGN HIGHLIGHTS

The operating concepts described in the previous sections of this report are functionally simple, and for the most part, were implemented using standard design techniques. However, a few design areas required very special, and in some instances, novel implementation methods worthy of special mention.

The simplified functional block diagrams of Figure 6 show the basic servo control feedback loops, and indicate that the summing amplifier has two inputs. The actual circuit has eight active parallel inputs:

1. the desired control signal (selected by the control selector)
2. the feedback control signal (selected by the control selector)
3. a velocity feedback signal for damping
4. a motor current feedback signal
5. the position limit override signal
6. the velocity limit override signal
7. the force limit override signal, and
8. a servo amplifier gain feedback signal.

The majority of these signals are non-linear in nature, and cannot be readily analyzed using classical feedback theory. However, design objectives were achieved by designing those circuits to ensure precise, stable d-c gain characteristics, and frequency responses well in excess of the frequency response of the basic servo circuits. The basic velocity feedback signal was derived from the filtered motor armature voltage, and adjusted for critical damping of basic servo response. Care was taken to ensure that the same open loop gain was achieved for the two basic operating modes to maintain the critical damping factor. The gain factors for the overriding limit functions are necessarily higher, resulting in an under-damped response, but this is desirable for these "emergency" conditions where response time is more important than accuracy. The motor current feedback is adjusted to permit three times the rated motor current to flow for brief transient high torque conditions, yet prevent excessive high current under long term stall conditions. This permits safe but efficient use of a relatively small motor.

The basic servo amplifier design is also unique, in that the motors are driven by switching transistors using a pulse-burst width modulation technique. The motors are 120 volt, 1/8 horsepower d-c continuous-duty industrial motors. For efficiency in the servo drive amplifiers, a pulse width modulation scheme was devised whereby switching transistors could apply full 120 volt pulses to the motor through a filter circuit, whereby the average voltage across the motor would vary depending upon the pulse width and motor load. The pulse repetition frequency is a constant 60Hz. This technique was complicated by the 240 volt (motor reversal) requirements imposed on the switching transistors. A series connected transistor circuit using present state-of-the-art 160 volt 10 amp transistors protected with 140 volt zener diodes was devised in a bridge arrangement to overcome this problem. To drive the transistors from the low voltage control circuits, the control pulses were modulated on a 5KHz carrier, and transformer coupled to the power transistors. The phasing of the 5KHz drive signals and the control pulses were chosen to eliminate the problem of inadvertent switching on of any but the appropriate pairs of transistors in the bridge circuit. Therefore the actual drive transistors are controlled by the width of a 5KHz pulse burst.

Another design innovation arose to meet the requirements for the limit circuits. A circuit was needed that would accept a bipolar d-c signal, and yield a linear output only when the input signal level exceeded a selected threshold level. A circuit was devised to provide this "electronic backlash" function, by incorporating two constant-current source circuits to provide balanced back-bias for a pair of series switching diodes. This useful circuit was employed as the logic element in all of the limit circuits, and for the force threshold operation.

The remainder of the circuit requirements were fulfilled using standard circuit designs, employing operational amplifiers and micro-logic elements wherever practical. Special care was taken to minimize the possibility of electrical shock in a hospital environment, by electrically grounding all exposed conducting surfaces to a common ground which is connected to the building ground.

3. PERFORMANCE EVALUATION EXPERIMENTS

A. GENERAL

This section of the report describes the experiments which were conducted to evaluate the performance of the two-axis Myotron, using both normal subjects and spastic subjects, in a research hospital environment. The purpose of this effort was not to obtain clinically valid data from the experiments, in the sense of subjecting a significantly large population to tests defined by a specific protocol. But rather, the efforts were primarily of a cut-and-try investigative research nature to determine suitable types of experiments to demonstrate the experimental utility and flexibility of the device. Any data obtained which may have medical significance requires further assessment and is not discussed in this engineering report.

This phase of the program was a team effort: the principal members being a Physiatrist and a Physical Therapist from the VA Hospital Research Staff, and the research engineers from the CAL staff. Support was provided as necessary from a VAH consulting physiologist, the Manual Arts Therapy Section, and other VAH services, as well as from the CAL technical and design shop services. As with any new tool, a great deal of learning was anticipated to be necessary. The medical team members were learning the operational principles and procedures of the Myotron, and the CAL engineering participants were learning the practical operational problems encountered with patients with various disabilities and the medical significance of potential experiments.

In general, the following practices were observed for each experiment involving subjects.

1. A physiatrist was present to observe and record the physiological status of the subject, to determine the safety limits desired, and for general consultation and direction
2. The pertinent force and position measurements were calibrated on the recorder, using known force and position standards.
3. The subject's entire body position was carefully adjusted, and was recorded by polaroid photographs.

4. The subject's passive maximum range of motion was determined and the position limits were set to prevent those limits from being reached.

5. The experiment was performed, maintaining a log of the activities and time.

6. A post-test calibration was recorded.

7. The recording was played back on a strip chart recorder, and the recordings marked to identify the date, subject, experiment, and calibration scale factors.

This set of general experimental guidelines was operationally satisfactory, and is recommended for future experiments.

B. SUBJECT ATTACHMENT AND FIXATION

The first operational experiments were devised to investigate the various methods of attaching the Myotron to the subject, and of fixing the body position of the subject. It was initially planned to use flexible inflatable pressure cuffs to secure both the wrist and upper arm in place, and simply to have the subject in a sitting position in a chair or wheel chair. The height of the Myotron "shoulder" from the floor had been chosen for a tall man in a wheel chair, intending to raise the chair with shims as necessary for shorter subjects.

The initial tests involved explorations of the various modes of operation, and the wrist pressure cuff was shown to be inadequate for any tests requiring substantial force measurements. The wrist is remarkably free of protective muscle or tissue and the air cuff would not act as a sufficient cushion for protection against the metal strain ring. Also, rather large thrust forces are developed involuntarily during certain procedures, and the pressure cuff would not adequately restrain the wrist from thrust motions.

A wooden split-ring cuff was devised, shaped in general to the surface of an average wrist. The length of the cuff was 2 inches, and this approach succeeded in distributing the forces over sufficient wrist area to allow maximum force to be exerted without discomfort. However, significant variations were found to exist in the shape and sizes of individual wrists, and a "universal" wooden cuff proved impractical.

This problem was adequately solved by moulding individual wrist casts for each subject from rapid-setting plaster. The casts were moulded to the shape of the subjects wrist using a plaster gauze which sets in less than 10 minutes, splitting and removing the cast, and then moulding the outside diameter with ordinary plaster to conform to a split steel ring which could be firmly attached to the strain ring. Figure 9 shows a subject fitted with this type of wrist cast.

A standard blood pressure arm cuff proved adequate to secure the upper arm within the metal sleeve of the Myotron, however, whenever the arm was flexed, the elbow joint itself was not well fixed, and could swing several inches with certain muscle contractions. To help stabilize the elbow, the inner ring of the Myotron upper arm support was re-fashioned with a cylindrical leather padded trough, which extended to the elbow along the location of the triceps muscle. This reduced the amount of elbow swing to less than one inch.

For the measurement of maximum strength, body fixation was found to be of primary importance. For example, a typical normal subject could exert a maximum flexion force (arm fixed at 90 degrees of flexion) of 35 pounds if the body and shoulder muscles were not allowed to be used, and 50 pounds if the use of the body and shoulder muscles was permitted. Furthermore, the same subject could, under the latter circumstances, withstand an external extension force of 85 pounds. The primary reason for this variation is due to an aspect of muscle physiology; that a skeletal muscle is much stronger in eccentric contraction than in concentric contraction. When this subject attempted to move the arm in the direction of flexion, actually a concentric contraction, he registered 35 pounds. When the subject was permitted to use his body and shoulder muscles, his tendency was to lock the elbow and use his body muscles to "pull" against the locked arm, putting his elbow stabilizing muscles in eccentric contraction, increasing his registered force to 50 pounds. Fixing his entire body against an external force further increased this effect.

Photograph courtesy of Veterans' Administration Hospital, Buffalo, New York

Figure 9 SUBJECT PLACEMENT SHOWING WRIST CAST AND UPPER ARM PRESSURE CUFF AND SUPPORT

The principal conclusions drawn from this study of body fixation were that the entire body position, support and restraint were of critical importance in the absolute measurement of the strength of any muscle group, and that no one body fixation method would be adequate for the different types of force measurement possible with the Myotron. Instead, the body fixation method should be left to the discretion of the experimenter for each particular experiment. In general, means should be employed to position each subject in the same repeatable position for a given experiment, perhaps with the aid of gentle restraint mechanisms. Attempting full restraint of the entire body would probably so alter the subject's physical and emotional status as to render any test data questionable.

One minor subject attachment problem arose which is worthy of brief mention. The carrying angle was not accounted for in the basic flexion extension axis design. The carrying angle is the natural offset angle between the upper arm and the forearm, greatest at full extension with the wrist in the full supination position. This angle varies from 10 to 20 degrees, and is generally greater in females than in males. Accommodation was made for the effect of this angle, (an internal thrust of the elbow joint when the arm is fully extended) by flaring the upper arm support trough to provide clearance for the epicondyle protrusion, which otherwise was a source of discomfort at full extension.

In summary, adequate attachment and fixation was provided by the use of the wrist cast, the upper arm inflatable cuff and trough support, and the use of a sturdy chair to position the subject. Care must be taken to note and repeat the entire body position and activity of the subject for a given experiment.

C. EVALUATION OF THE SERVO CONTROL AND LOGIC FUNCTIONS

All individual servo control and logic functions were examined under test, and some changes were incorporated to improve the operational performance of the Myotron. In general, however, it was found that the basic operating controls and operating ranges were adequate for the intended experiments.

In the position-following servo modes, the only difficulty encountered was with a resonant chatter at certain velocities when the motion was being aided by a force from the subject. This was caused by a combination of gear backlash, irreversibility of the worm drive, and spring in the flexible shafts. This resonance phenomona was eliminated by increasing the inertia of the worm gears by adding flywheels to the worm gear shafts. These small flywheels also served as manual positioning knobs for moving the arm with the power off.

A more basic problem was encountered in the force-following mode of operation. Basic instability was found to occur in the high sensitivity force-following operations. The nature of the instability varied with the individual subject, and was, in general, more severe for subjects with large fleshy forearms. The basic frequency of the instability was approximately four or five cycles per second with the forearm and hand muscles relaxed, and would increase to twelve to fifteen cycles per second with the muscles tensed. The principal reason for this effect is that in the force-following mode, the mass of the arm is the controlled element, and the displacement must be considered with respect to the center of mass, not the center of the bone structure at the wrist. Since the mechanical arm is tightly coupled to the bone structure at the wrist, the actual load is connected to the drive through a varying spring constant determined by the rigidity of the muscles and flesh.

To avoid this instability in the high sensitivity mode, a 2 Hz low pass filter ("flab" filter) was inserted into the feedback path of the servo control loop. This filter does not effect the response of the recorded force signals, but does prevent the resonant instability from occurring during force-following operations. The response of the system remains adequate for normal force-following studies.

One front panel control was changed to increase the flexibility of the instrument. The sensitivity of the force meters and controls were originally determined by a two position switch, allowing for either 100 pounds full scale sensitivity in the NORMAL position or 5 pounds full scale sensitivity in the MAXIMUM sensitivity position. This switch control was replaced with a pair of continuous dial controls for individual flexion-extension and rotation sensitivity adjustment at any level from 3 to 100 pounds full scale. The dial settings read approximately in pounds, and a calibration curve is used for setting exact sensitivities.

Another minor operational feature was added to enable playback of recorded experiments at a remote location. A conversion cable was made to permit the operator console and recorder unit to receive line power and function normally without being connected to the arm and support table. This was added as a convenience to allow the portable console to be wheeled to any remote facility for playback of the recorded data on a strip chart recorder.

The principal conclusion of the evaluation of the servo control and logic operations is that the Myotron operating principles are basically sound. Particular attention must be given to the nature of the mechanical load mass characteristics in a force-following system of this type.

D. EVALUATION OF EXPERIMENT PROCEDURES.

To evaluate the operational effectiveness of the two-axis Myotron, three simple single-axis experiments were designed for the measurement of certain spasticity parameters in hemiplegic subjects: static force measurements, active range of motion measurements, and constant velocity measurements of relaxed arm residual forces.

1. Static Force Measurements

To examine the basic operating characteristics of the force measurement portions of the instrument, an experiment was designed to obtain maximum force characteristics of the elbow flexor-extensor muscles as a function of elbow flexion angle. The arm was positioned to five discrete flexion angles, starting near maximum extension, and progressing 30, 60, 90 and 120 degrees. At each position, the subject was requested to exert a maximum force in flexion, holding for 3 seconds. A number of trials, usually three, were performed, and then repeated in the extension direction, with suitable rest intervals between trials. The results were plotted as continuous force versus angle curves, as well as discrete vector forces for each angle position.

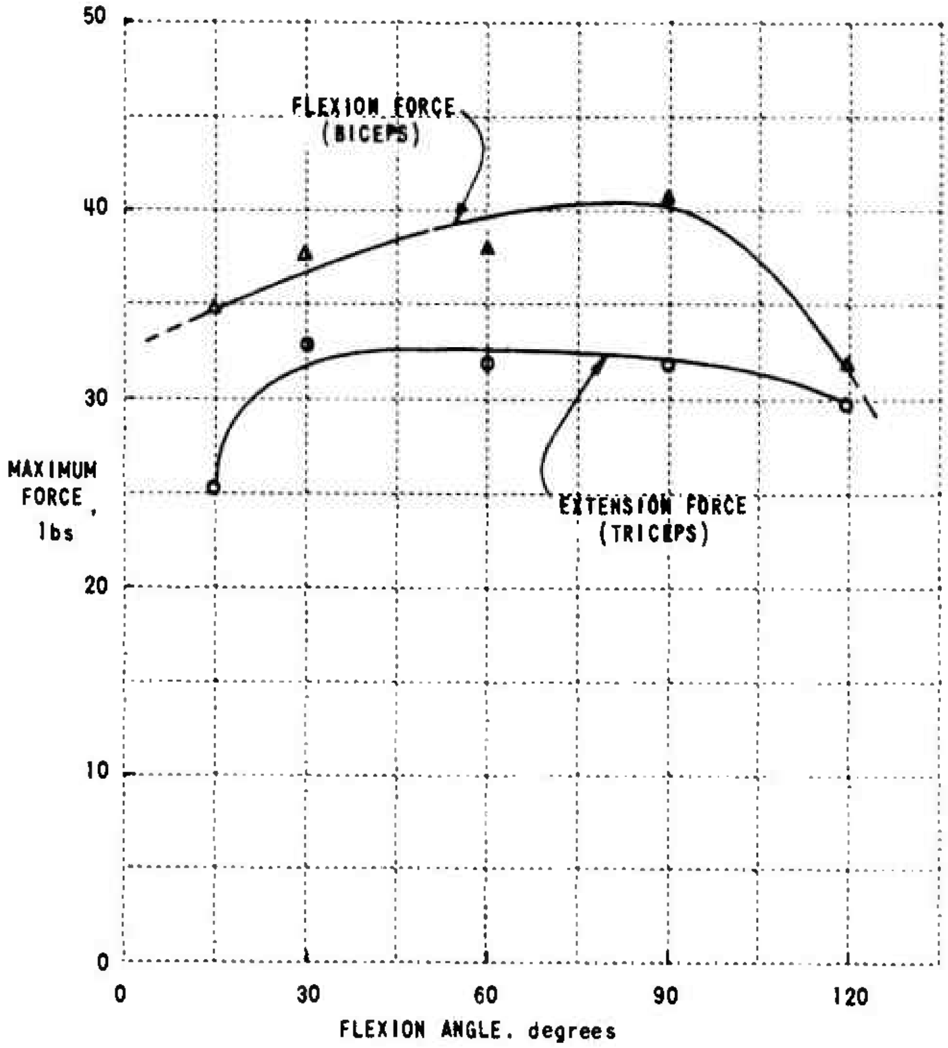
Figure 10 shows the standard method of presenting the measured data, which accounts only for the force component in the flexion or extension direction. Figure 11 shows one method of displaying the information as a vector force. In this instance, the magnitude of the force is indicated by the magnitude of the vector arrow, and the direction of the force is indicated by the direction of the vector arrow. The orientation of the polar plot is the same as viewed when looking at the subject's right hand in line the the forearm.

Figure 12 shows the behavior of the vector forces as a function of flexion angle for three normal subjects and one hemiplegic subject. Normals A and C controlled the flexion force direction very accurately, whereas normal B indicated a marked tendency toward internal rotation as the flexion angle increased. The hemiplegic subject's force levels were considerably less in magnitude, consistently favored external rotation during attempts at flexion, and were completely disoriented in attempts at extension. The diagrams show that although the subject was attempting to extend, the actual force exerted was in the flexion direction. The subject could not see the force meters, and actually thought that he was directing the force in the extension direction. The residual forces returned to less than two pounds between the force attempts.

Figure 13 shows the recorded raw data as played back on a strip chart recorder. In this form, the time history of the muscle tension is clearly shown. This subject tended to increase tension rapidly at first, then slowly approach the maximum, and rapidly relaxed to zero. The residual force between attempts is principally due to the weight of the subject's arm and cast. The transients on each trace indicate that the recorder was stopped during the rest intervals between trials.

2. Active Range of Motion Measurements

To examine the utility of the force-following mode of the instrument, an experiment was devised to measure the unaided active range of motion in the flexion-extension axis. The shoulder was rotated to the anatomical zero position, with a 90 degree flexion angle to allow the elbow flexion-extension motion to sweep over a horizontal plane. This position



Note: Normal Subject

Figure 10 STANDARD PRESENTATION OF MAXIMUM FLEXION-EXTENSION FORCES vs FLEXION ANGLE

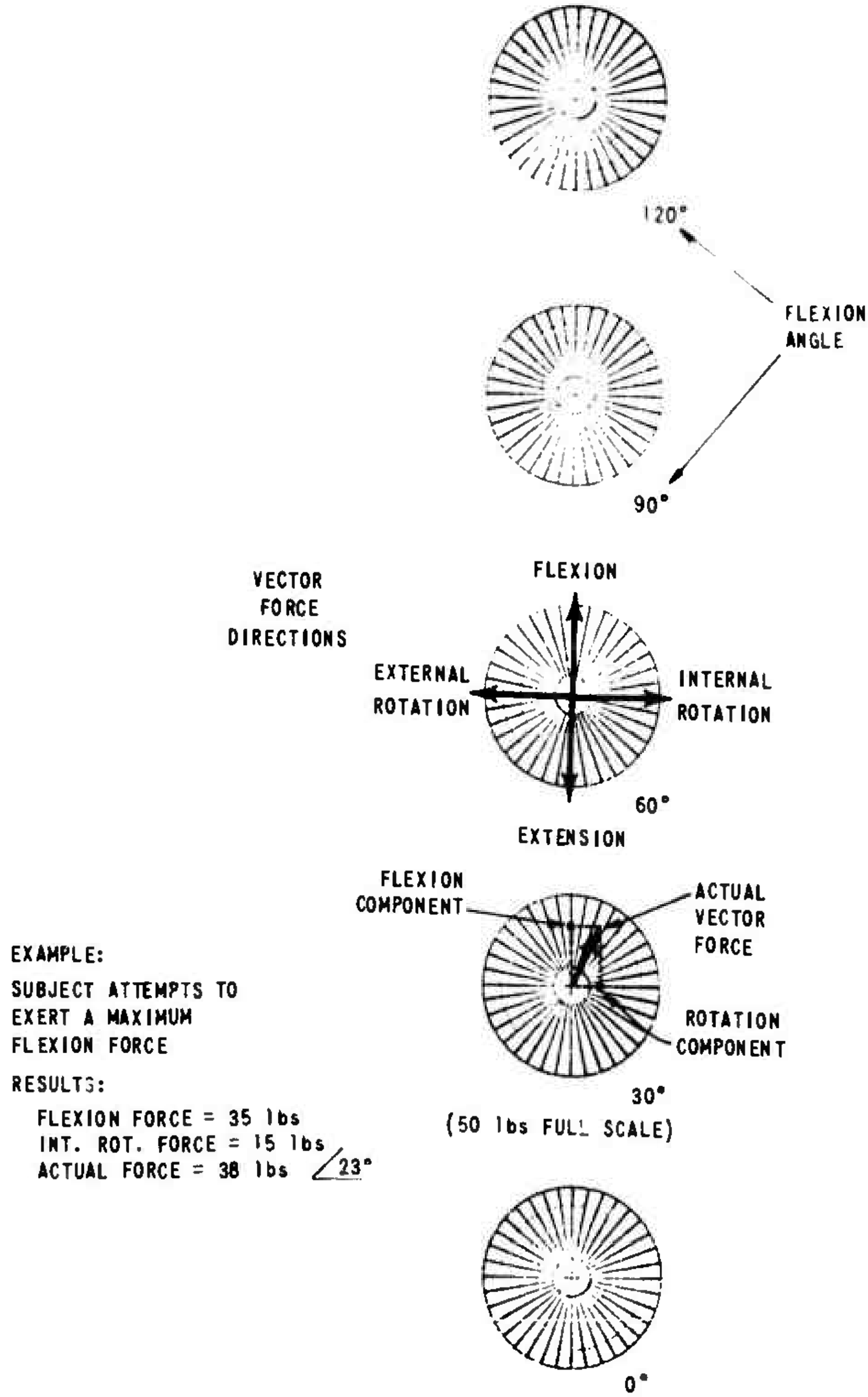


Figure 11 KEY TO VECTOR FORCE PRESENTATION

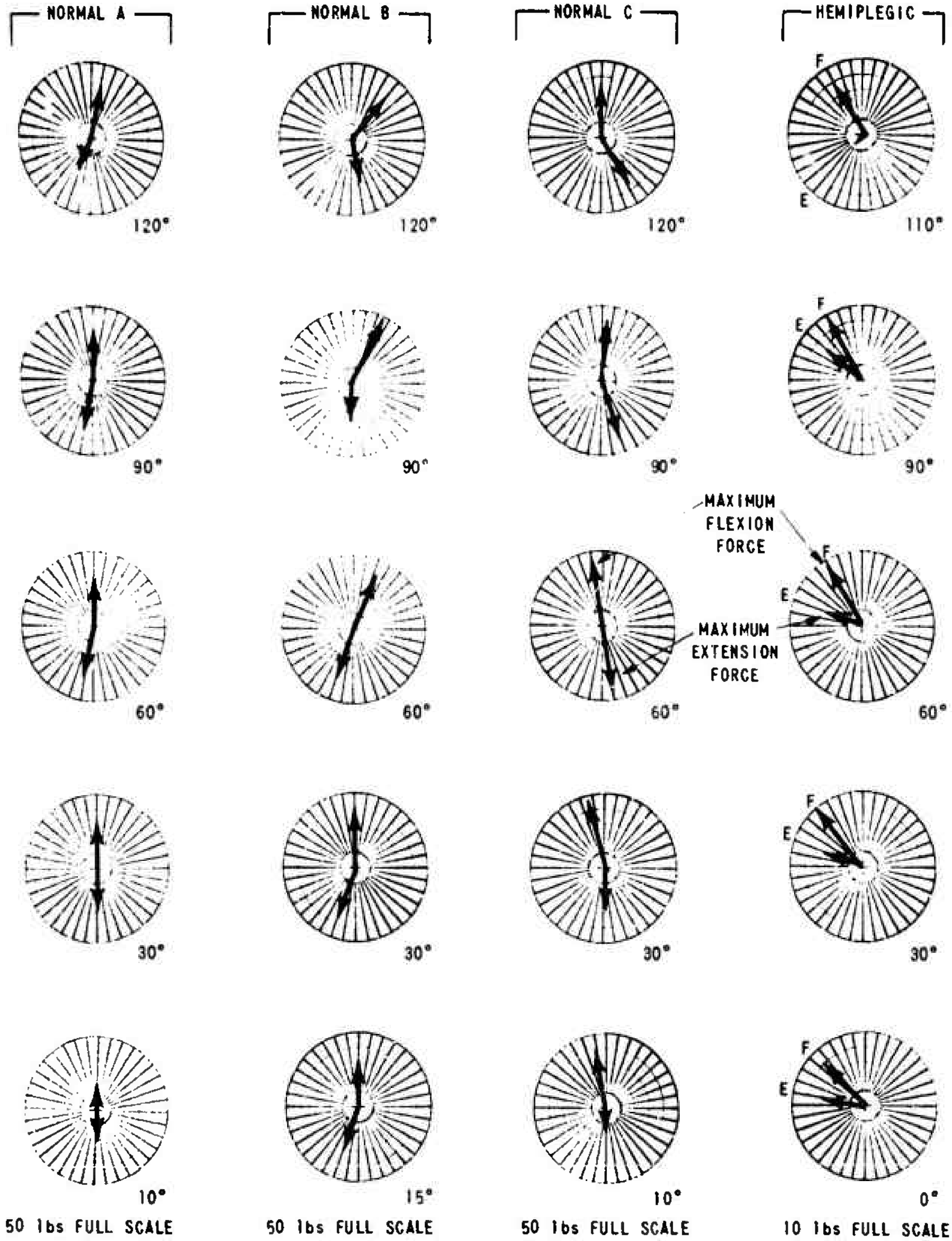


Figure 12 MAXIMUM FLEXION-EXTENSION VECTOR FORCES -- 3 NORMAL SUBJECTS, ONE HEMIPLEGIC

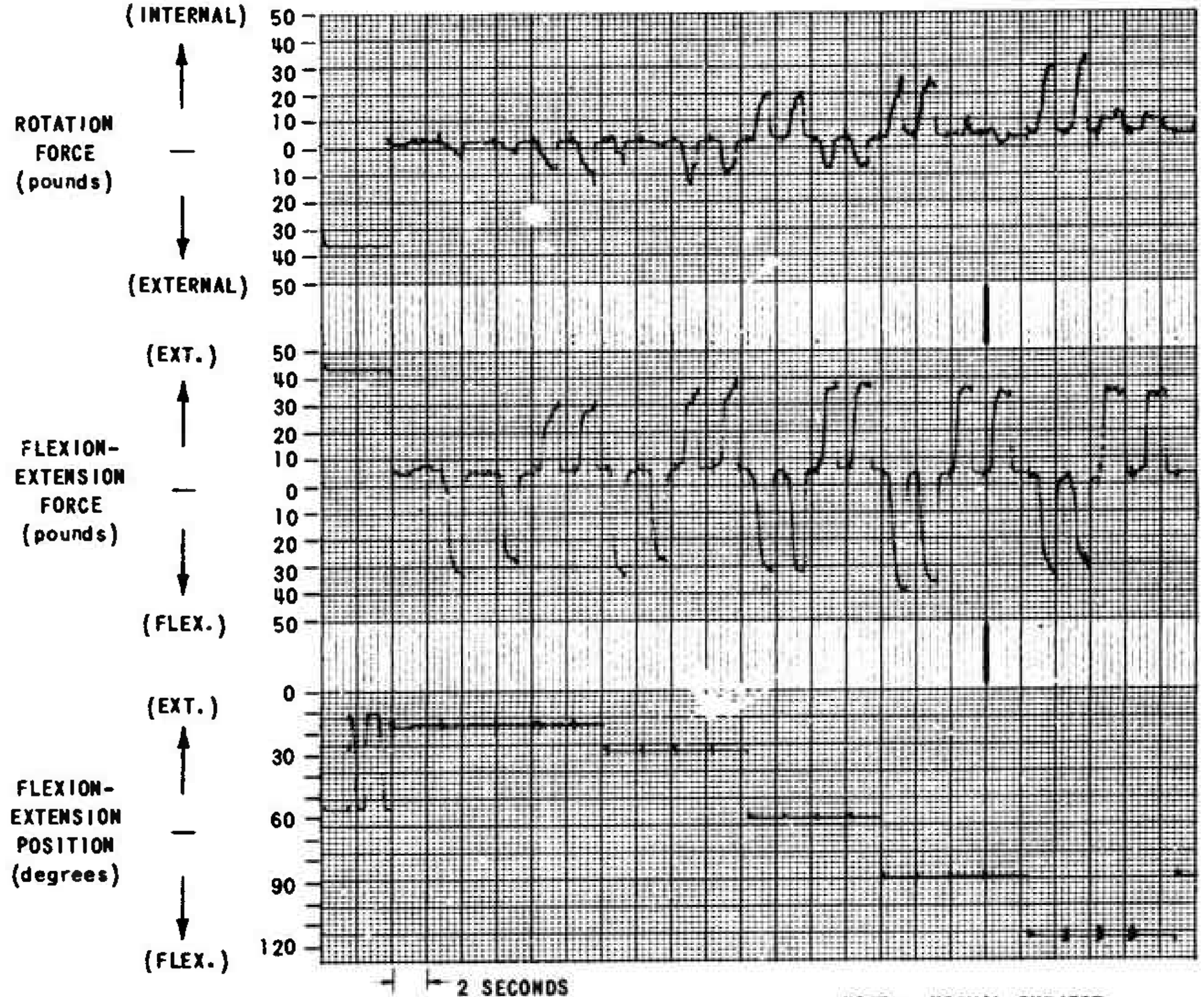


Figure 13 MEASURED MAXIMUM STATIC FORCES -- TYPICAL PLAYBACK FORMAT

eliminates the force variation due to a changing weight vector as the elbow is flexed.

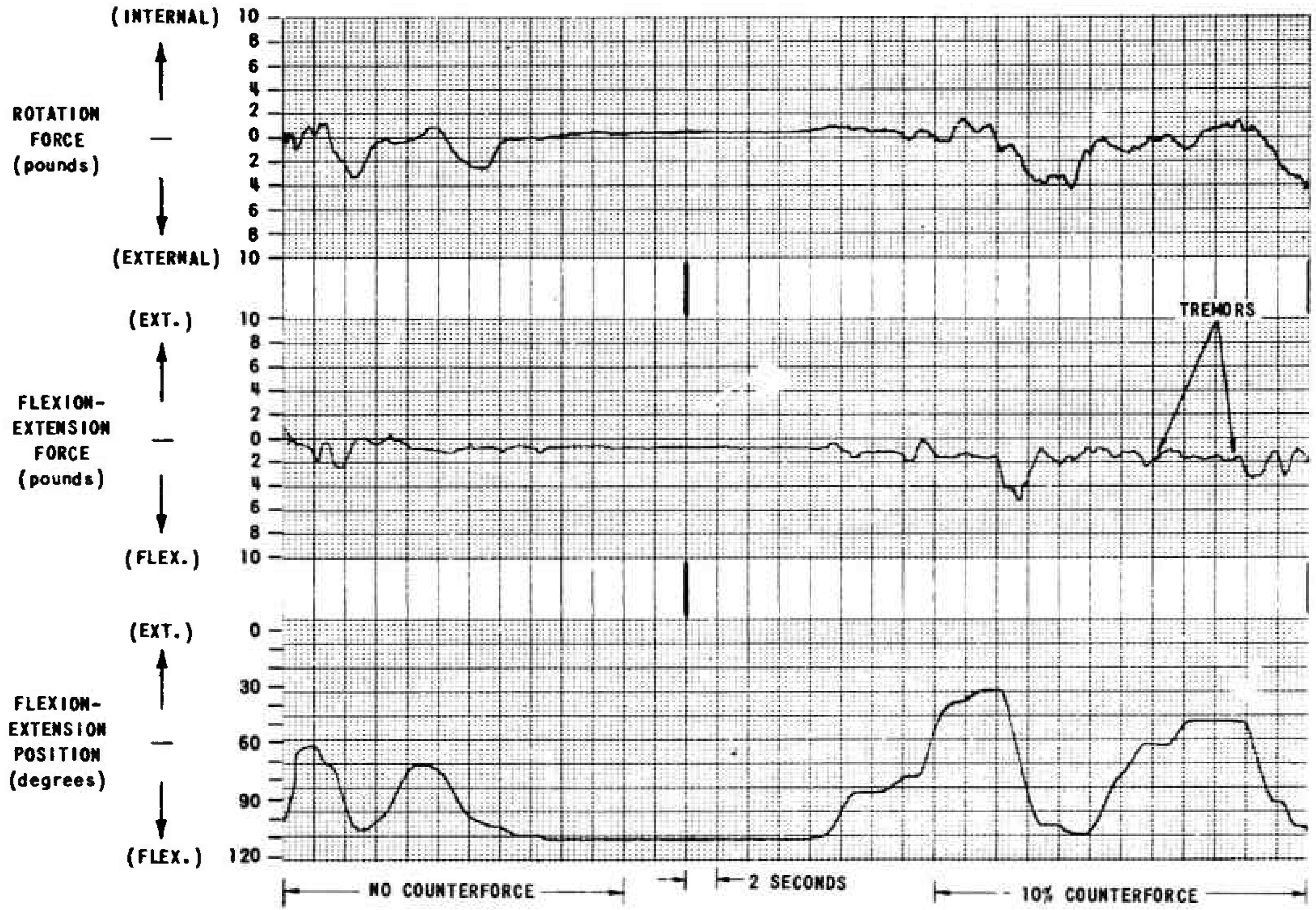
The behavior of a hemiplegic subject is shown in Figure 14. (Normal subjects, of course, could control the arm over the full range between the position limits.) The subject was instructed to move his arm as far as possible in each direction. Repeated trials resulted in a maximum excursion of about plus and minus 25 degrees from the anatomical 90 degree position for this particular subject.

With the subject's arm relaxed, a counterforce was added in the extension direction, causing the arm to extend to a position where the counterforce was balanced by the subject's natural rigidity force, and the subject was again requested to move his arm as far as possible in each direction. The latter portion of the record shown in Figure 14 shows the increase in range of motion attained with the addition of a 10 percent counterforce (in this case, 1 pound). The counterforce was increased to 15 percent, at which point this subject could control his arm over the full 0 to 120 degree range. With only a few minutes of practice, he was able to follow motions indicated by the therapist, and to select and hold specified angles.

Note the two tremor oscillations indicated by the arrows in Figure 14. This portion of the tape recording was played back again on the chart recorder at a higher chart speed and gain setting to amplify the tremor detail, as shown in Figure 15. These two tremors occurred when the arm was at rest, negating the possibility of a machine artifact, and have a basic frequency of 12 Hz.

3. Constant Velocity Measurements of Relaxed Arm Residual Forces

An experiment was devised to demonstrate the measurement of spastic rigidity forces as a function of passive arm movement. The subject was requested to neither aid nor oppose the motions of the machine, and various combinations of flexion-extension movements at constant velocities were performed. The amplitude of the movement was varied from a very small deviations from the 60 degree position, to deviations over nearly his full range of motion. The direction of motion was reversed instantly at each extreme for some tests, and stopped for a short pause in other tests. A



NOTE: HEMIPLEGIC SUBJECT, FORCE FOLLOWING IN FLEXION-EXTENSION, LOCKED IN ROTATION

Figure 14 TYPICAL RECORDING OF ACTIVE RANGE OF MOTION

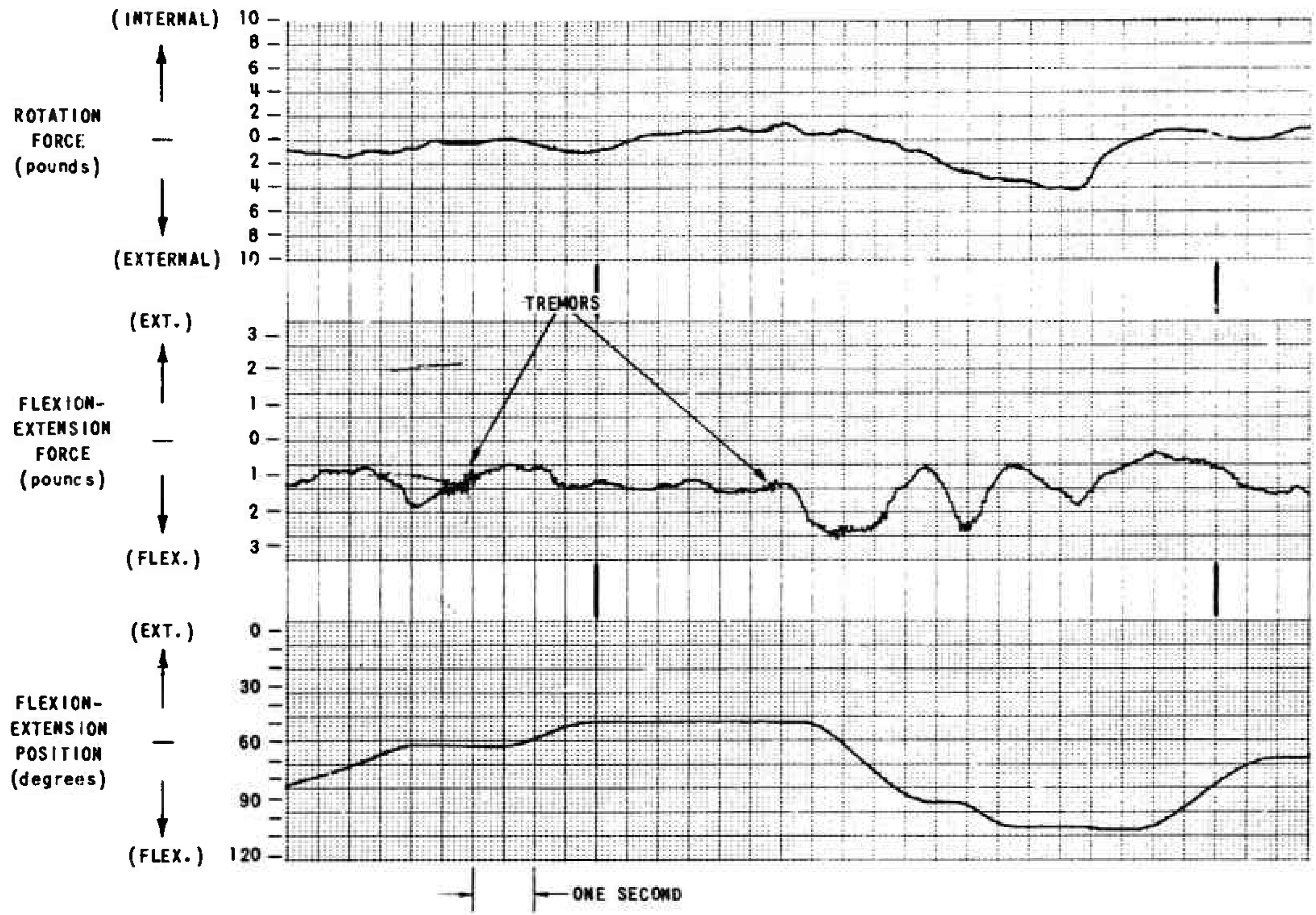


Figure 15 EXPANDED RECORD SHOWING DETAILS OF THE TREMORS MARKED IN FIGURE 14

constant velocity was achieved by having the device follow an external position command generated by a triangular wave function generator. The involuntary forces present as a function of flexion-extension position, velocity and acceleration are measured. As in the range of motion measurements, the flexion-extension sweep was in the horizontal plane, avoiding the gravity vector effect.

Figure 16 and 17 show the comparative forces exhibited by a normal subject and a hemiplegic subject at relatively slow velocities. The normal subject residual force is less than 0.5 pounds in all instances (or approximately 1 percent of his maximum capability), whereas the hemiplegic subject exhibits a flexion-extension force pattern much like that of a spring, with amplitudes approaching 2 pounds (or approximately 25 percent of his maximum capability), where the force is proportional to the deflection. When the arm is halted at the position extremes, the force remains at a constant level, indicating that the force is primarily due to the arm position, and not the velocity. A distinctive pattern is exhibited by the record of the rotational force component, although no motion in the rotation axis had occurred.

Figures 18 and 19 show the same comparison at a higher velocity. The normal subject's force trace shows the inertia effects of rapidly stopping and starting the limp arm, but the average forces during travel are nearly zero. The hemiplegic subject exhibits the same basic force pattern as at the slower velocity, with less inertia effects than those shown by the normal subject's force record, perhaps due to the continuous muscle tension.

Figure 20 shows the same hemiplegic subject two days later. No attempt was made to determine the cause of the change in response indicated, other than to carefully ascertain that the experiment conditions were the same. Note that the rotation force component pattern has also changed markedly. The most significant portion of this new force behavior is that although the arm movement stops for nearly 0.8 seconds at the flexion extreme, the opposing force does not remain a constant as before, but continues to a peak value of nearly twice the previous level. The cause of this reflex contraction has not been sought, and appears worthy of further investigation.

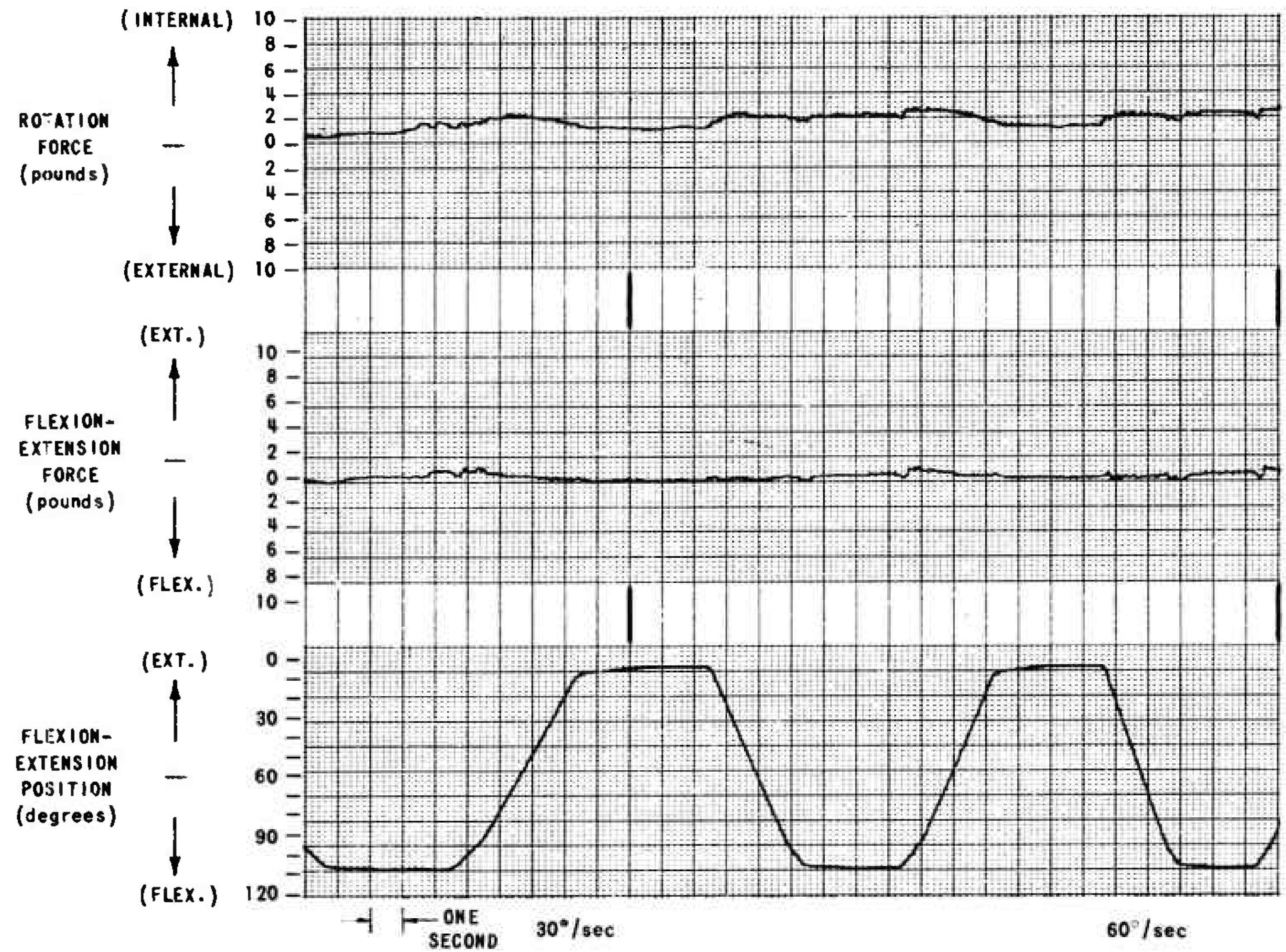


Figure 16 CONSTANT VELOCITY TESTS -- NORMAL RELAXED ARM SHOWS NEGLIGIBLE RESISTING FORCE

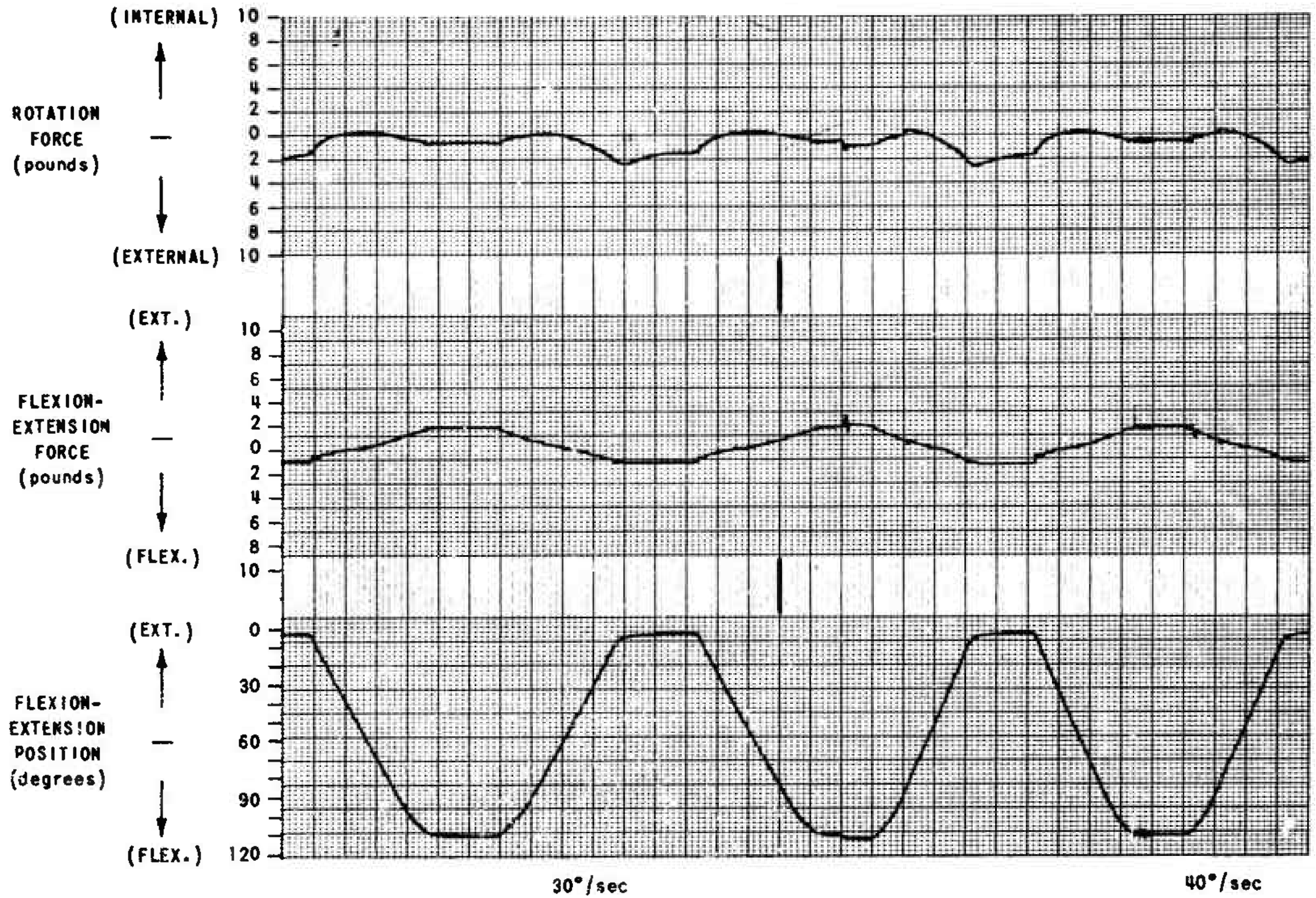


Figure 17 CONSTANT VELOCITY TEST -- RELAXED ARM OF HEMIPLEGIC SUBJECT SHOWS SPRING-LIKE RESISTING FORCE

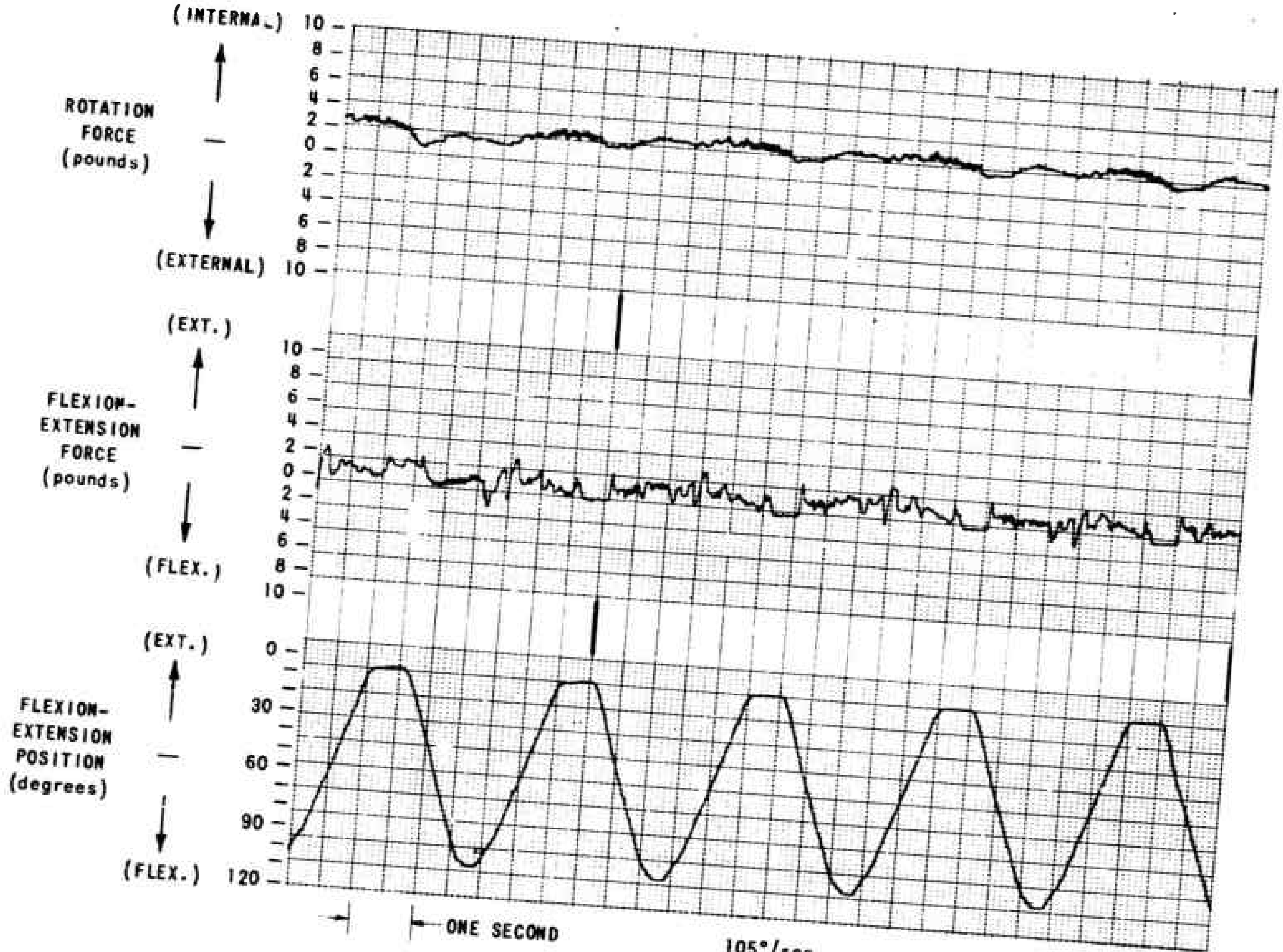


Figure 18 NORMAL SUBJECT AT HIGHER VELOCITY

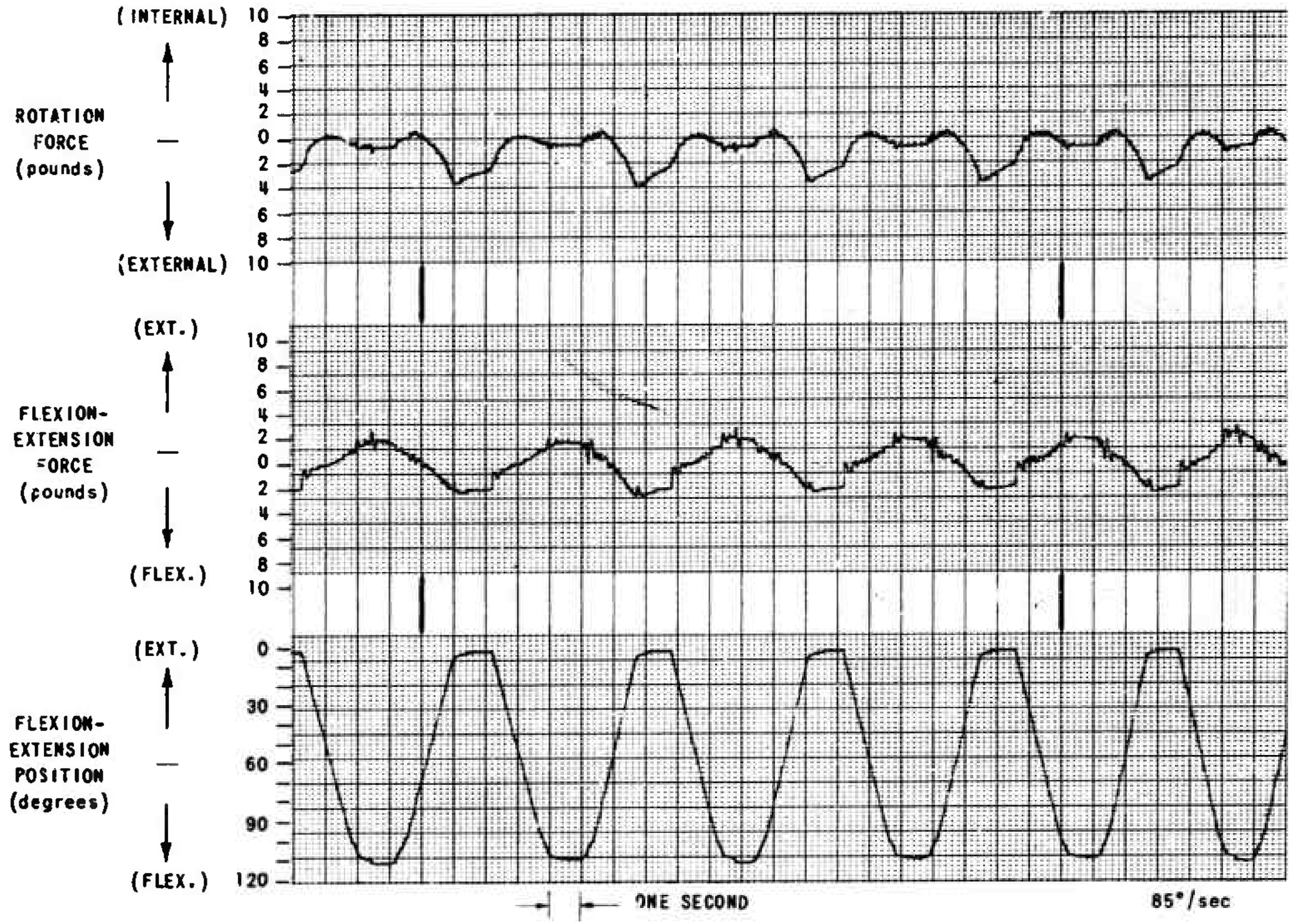


Figure 19 HEMIPLEGIC SUBJECT AT HIGHER VELOCITY

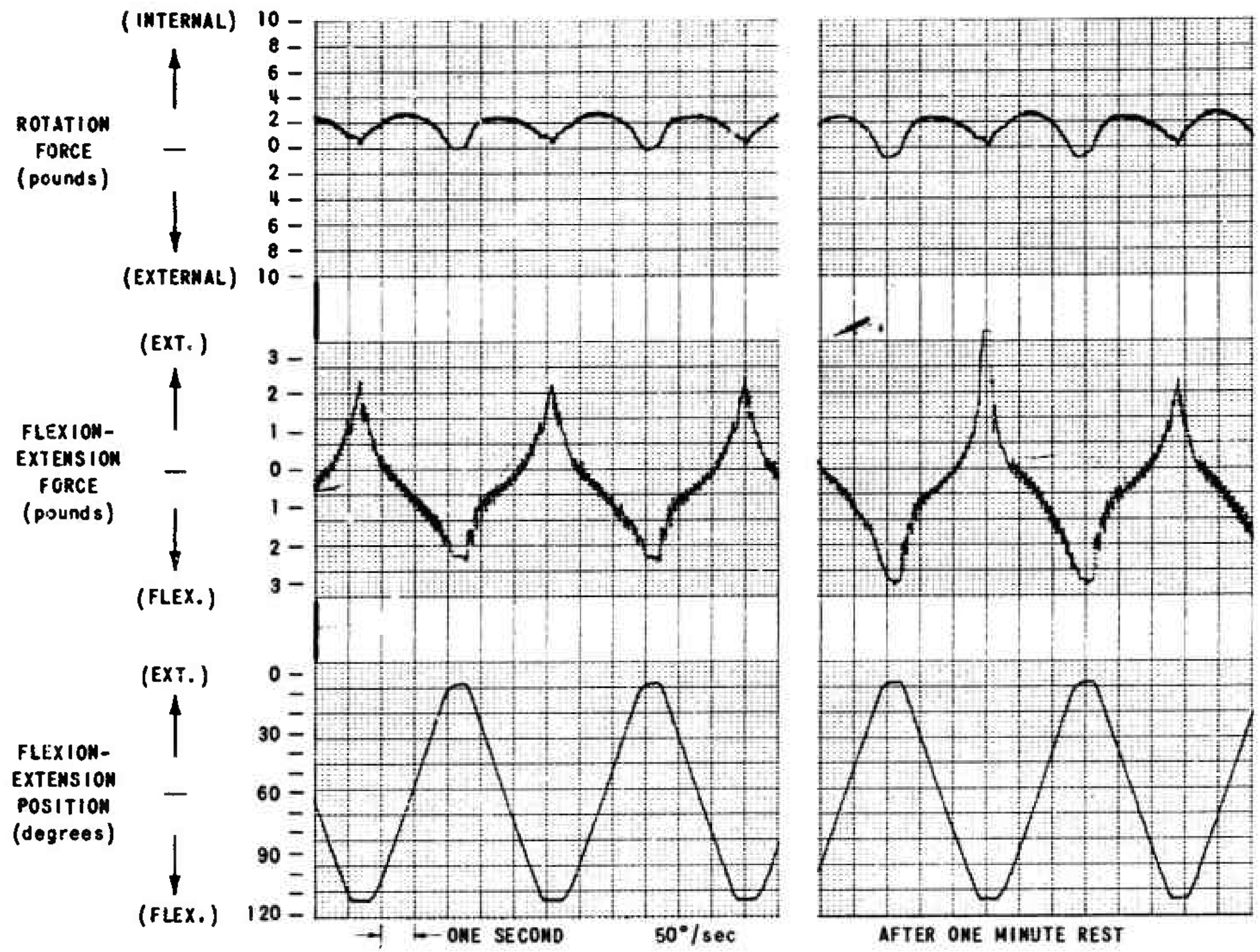


Figure 20 SAME HEMIPLEGIC SUBJECT AS IN FIGURE 19 ON DIFFERENT DAY SHOWING A FORCE REFLEX AT MAXIMUM FLEXION

These three experiments indicate primarily that this instrument is capable of measuring spasticity forces under controlled conditions, and has the potential for revealing details of muscular behavior in a unique new form.

4. CONCLUSIONS AND RECOMMENDATIONS

The Myotron, as implemented in the present two-axis instrument, has been shown to be technically practical and conceptually valid. The measurement of dynamic muscular forces with a servocontrolled exoskeleton is a powerful new research technique for the study of neuromuscular behavior. The experience gained by the development and evaluation of this two-axis instrument, however, indicates that the extension of this concept to a full-body Myotron, even if limited to a 33-axis exoskeleton, would be a major undertaking. Although development of the full-body Myotron is technically possible today, the operational complexity and data reduction problems appear to question the utility of this approach. Further operational experience with a less complex instrument is desirable before developing a full-body unit. The use of a Myotron with up to, say, four controlled axes, is undoubtedly practical for the study of additional limb movements and muscle groups. The present two-axis Myotron can be used to obtain much valuable information for effective development of an eventual full-body device.

Specifically, this research program has revealed that the man-machine interface problems are not as severe as expected. The body attachment and fixation techniques devised are simple and adequate. No adverse subject reaction to being restrained in this mechanical device was encountered, and neither the noise nor the "feel" of the machine interfered with the subject's ability to perform the required tasks and procedures. Under all circumstances incurred during this 3-month evaluation program, the safety measures proved adequate in protecting the subject from unintended motion extremes. Interference with other sensitive electrical instruments, particularly with an electromyograph attached to the subject, was not detectable. The operational flexibility and measurement sensitivity and accuracy proved adequate for the type of experiments necessary for the study of neuromuscular disorders. In particular, fatigue tremors were often recorded routinely, and illustrate the potential for quantitative assessment of tremor severity.

The general working knowledge gained about the operational capabilities of the instrument indicate that a wide variety of neuromuscular research experiments are practical. Although the evaluation experiments were limited in scope, the direct results of these experiments suggest three particular research areas of sufficient importance to warrant further study.

1. basic research studies of flaccid and spastic paralysis muscular behavior, for detecting the participation of specific muscles or muscle groups, for diagnosing the nature of the disorder, and for observing the effects of drug or therapy treatments.

2. research studies of new therapy techniques in the management and control of spasticity, particularly in the area of patient-controlled coordination movement exercises using the counterforce aided force-following mode of operation (From an engineering standpoint, this type of therapy should be as effective as speech therapy in the rehabilitation of stroke victims because it would allow natural feedback to the central nervous system of all the limb activity sensors, and thus enhance the formation of new command processes.)

3. research studies to determine and evaluate the problems to be encountered in applying the force-following technique for developing micro-force following powered orthotic devices.

These research activities can be pursued using the present two-axis Myotron. However, it is recommended that modifications in the mechanical structure be considered to improve the accuracy and reliability of the present feasibility model. Specifically, the strain-ring should be re-fabricated using a less lossy spring material to reduce the hysteresis effect (presently about 4 percent for maximum loads and 10 percent for one pound loads), and incorporating a larger wrist opening to facilitate the passage of the typical clenched fist of the spastic subject. In addition, an improved drive mechanism should be considered to reduce gear cogging effects and increase the torque transmission efficiency (presently 30 percent, but could be 90 percent).

Future development efforts for constructing other Myotron instruments should consider incorporation of the following:

1. electronic analog computer circuits to automatically counterbalance the limb gravity forces in the force-following mode,

2. lighter weight attachment fittings at the force sensing points to minimize inertia effects, and

3. an integral adjustable body support mechanism.

Further experience with the present instrument will undoubtedly result in additional recommendations for design improvements.

In summary, this research program has demonstrated the utility of the Myotron concept and provided medical researchers with an instrument with potential for revealing new information about the nature of neuromuscular activity.

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